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GASEOUS FUEL REACTORS FOR POWER SYSTEMS

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ABSTRACT

The Los Alamos Scientific Laboratory is participating in a NASA-sponsored program to demonstrate the feasibility of a gaseous uranium fueled reactor. The work is aimed at acquiring experimental and theoretical information for the design of a prototype plasma core reactor which will test heat removal by optical radiation. The basic goal of this work is for space applications, however, other NASA-sponsored work suggests several attractive applications to help meet earth-bound energy needs. Such potential benefits are: small critical mass, on-site fuel processing, high fuel burnup, low fission fragment inventory in reactor core, high temperature for process heat, optical radiation for photochemistry and space power transmission, and high temperature for advanced propulsion systems. Low power reactor experiments using uranium hexafluoride gas as fuel demonstrated performance in accordance with reactor physics predictions. The final phase of experimental activity now in progress is the fabrication and testing of a buffer gas vortex confinement system.

FOR MANY YEARS the National Aeronautics and Space Administration has supported research and development programs on nuclear systems for space applications. One of these programs is an advanced reactor concept, a gaseous fuel nuclear reactor. The research branch of the U.S.-NASA, Office of Aeronautics and Space Technology, is conducting a program of research directed at developing the technology necessary for a multimegawatt uranium plasma core reactor. Although the basic goal of this work is for space application, other NASA-sponsored work suggests several attractive applications to help meet earth-bound energy needs. (1)* Operation of a reactor core at uranium plasma temperatures opens the possibility of working systems with higher thermodynamic efficiencies than conventional reactors. Recent interest in the gaseous fuel reactor concept has expanded to include the use of uranium hexafluoride instead of uranium plasma as the fuel. With uranium hexafluoride as fuel, applications other than rocket propulsion are possible: the most significant is power, both in space and on earth.

*Numbers in parentheses designate References at end of paper.

The major design features of the gaseous core reactor are a reflector moderated cavity containing fissioning plasma that is isolated from the cavity walls by hydrodynamic forces of an inert buffer gas. Reactor control is accomplished by rotatable control drums located in the reflector, and adjustment of the power is accomplished by two methods. A heat exchanger of conventional concept is used to cool the gases that are recirculated through the cavity. A second method is the removal of radiant energy (photon flux) through an optically transparent port. Attention is drawn to three fundamental features of the gaseous fuel reactor system which are: (1) gaseous flowing fuel, (2) the high neutron economy of the reflector moderated cavity, and (3) the possibility of nonequilibrium optical radiation (i.e. optical radiation differing from the Maxwell-Boltzmann distribution of the characteristic core temperature). These features make possible some beneficial characteristics such as (a) small critical mass, (b) fuel circulation and on site processing, (c) burnup of transuranium actinides, (d) high fuel burnup, (e) high power generation efficiency, (f) breeding of U233 from thorium, (g) low fission fragment inventory in reactor core, (h) high temperature for process heat, (i) optical radiation for photochemistry and space power transmission, and (j) high temperature for advanced propulsion systems.

BACKGROUND

As early as 1955 consideration has been given to the possibility of producing nuclear energy by fissioning fuel in the gaseous state. (2,3) Following the detailed development of reflector-moderated reactors (4) significant confirmatory experiments were performed. (5) This sequence of work on spherical systems emphasized the importance of designing a system having a very high neutron economy. It demonstrated that benchmark experiments were very valuable accompaniments to the development of calculational methods needed to predict reactor performance. Additional research performed on cylindrical geometries is substantive for calculational verification. (6,7)

URANIUM HEXAFLUORIDE EXPERIMENTS

A program was instituted to demonstrate the feasibility of a gaseous U235F6 reactor of cylindrical geometry.(8) The program is being conducted by investigation of critical configurations at the Los Alamos Scientific Laboratory and the development of uranium hexafluoride handling techniques and equipment by the United Technologies Research Center. Maximum utilization is being made of equipment and technology developed for the solid core nuclear rocket engine program (ROVER). Figure 1 is a schematic of the reactor experiment.

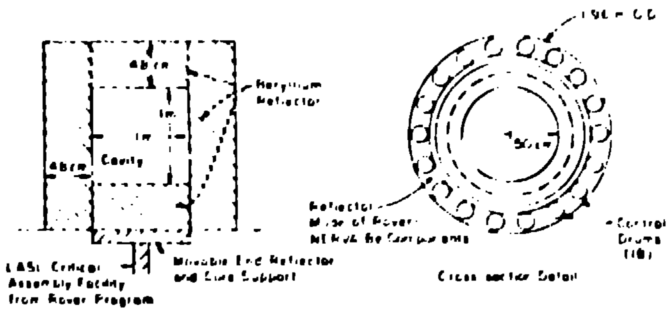

Fig. 1 - Beryllium reflected gas core reactor experiment

INITIAL EXPERIMENTS established the critical neutronic characteristics of the cylindrical gas core configuration. Zero power mockups were constructed using uranium foil to achieve the first criticality. Power distribution measurements were performed, control rod calibrations made, and reactivity worths determined for various structural materials. These initial scoping experiments were performed in a sequence of four steps. The first step was a configuration of the uranium foil arranged in a homogeneous distribution throughout the one meter diameter by one meter tall cavity of the reactor. The critical mass for this configuration was found to be 19 kg of 93.2% enriched uranium. The second step was a redistribution of the fuel to provide a uranium foil liner of the cavity. The critical mass remained about 19 kg as predicted by calculations. The third step was to add a beryllium flux trap resulting in a configuration which was critical with only 6.84 kg. The fourth, and final step, of this series was to provide a configuration whereby a canister containing uranium hexafluoride gas could be inserted in the center of the cavity region. This was accomplished by surrounding the beryllium flux trap annular ring with solid fuel.

STATIC GAS FILL EXPERIMENTS - The scoping experiments were followed by investigations using uranium hexafluoride gas. A canister was pressurized with uranium hexafluoride gas, inserted in the Be reflector, and critical measurements performed. The first phase is referred to as the static fill experiment and the equipment is diagrammed in Figure 2. Figure 3 shows the actual canister and gas handling system removed from the reflector assembly. A number of critical tests were made where additional uranium hexafluoride was added to the canister. Reactivity was adjusted by the removal of solid fuel from the exterior of the flux trap ring to compensate for the addition of gaseous fuel. Results of these experiments showed that no radiation induced chemical instabilities were produced by runs up to 1000 watts. In addition, experience was gained in the techniques required for the handling of uranium hexafluoride gas at somewhat elevated temperatures.

FLOWING GAS EXPERIMENT - The next phase of work with the gas system was to perform experiments with recirculating uranium hexafluoride. A system was constructed to produce gas recirculation in race-track closed loop fashion. Its purpose was to investigate the effects on reactivity caused by fluctuations in

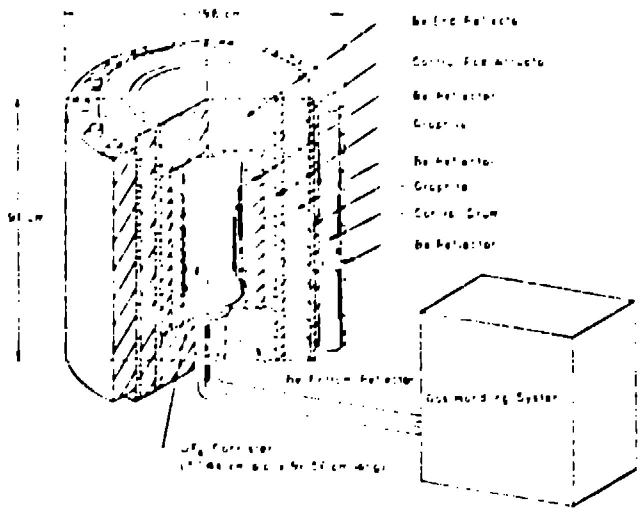

Fig. 2 - Gas Reactor Experiment

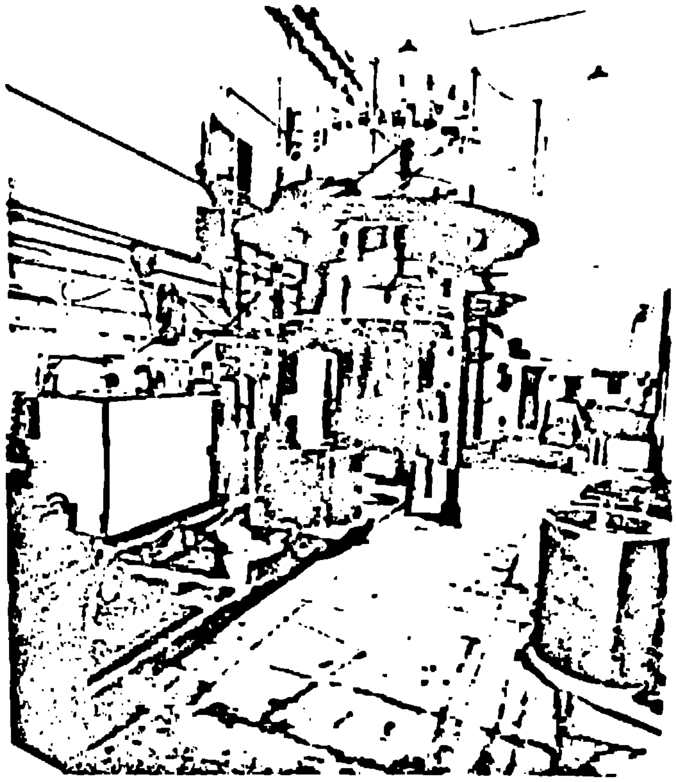

Fig. 3 - Canister and gas handling system

either gas flow rate or in the gas pressure. The equipment used in the flowing gas experiment is shown in Figure 4. The canister is shown connected to the gas handling system by flexible lines and is raised into the reflector to perform the critical tests. As was the case on the static experiment, this system was equipped with double wall containment. Hot nitrogen gas circulated through the outer

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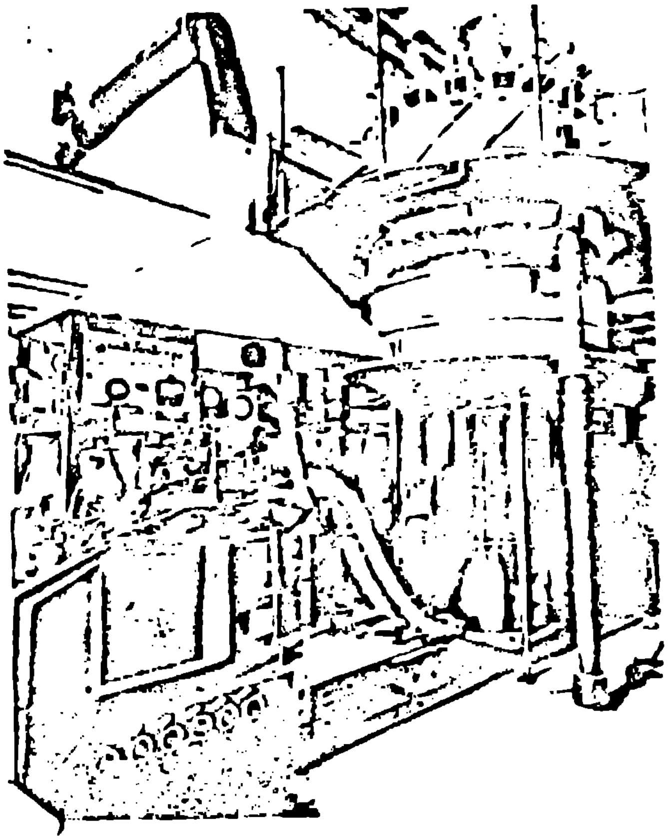

Fig. 4 - Flowing gas experiment equipment

wall cavity and maintained the uranium hexafluoride gas at an appropriately high temperature.

TEST RESULTS - The static experiments showed us that, from reactivity considerations, there would be an advantage in configuring the reactor design such that the gas would be contained in seven cells - a central cell surrounded by six others. Figure 5 illustrates this concept. The experiments are thus a mockup of the central cell. Monte Carlo calculations predict a critical mass for this configuration of approximately 4.9 kg. The target of the recirculating gas experiment was to have a uranium inventory of 700 g in the canister. For safety reasons, the initial tests of the recirculation systems were conducted with a uranium hexafluoride inventory of approximately 30 g and a mass flow rate of 1.2 g/second. The fuel loading mass flow was increased in a stepwise fashion to the final values of 700 g and mass flow rate of 50 g/second.

HYDRODYNAMIC CONTAINMENT TESTS - The final phase of the experimental program calls for the demonstration of buffer gas vortex flow confinement of the fissioning uranium hexafluoride fuel. The cutaway diagram shown in Fig. 6 illustrates the flow pattern for this test, while Figure 7 is the gas handling system, and Figure 8 is the reactor core canister. Argon buffer gas is injected through the slot shown along the length of the fuel canister. Most of the argon

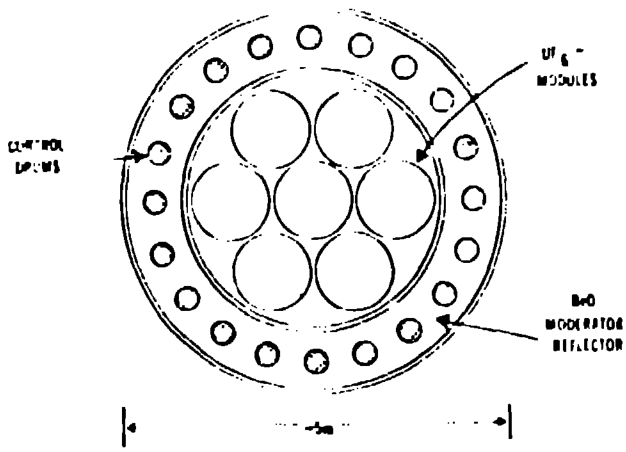

Fig. 5 - Self-critical uranium hexafluoride reactor experiment

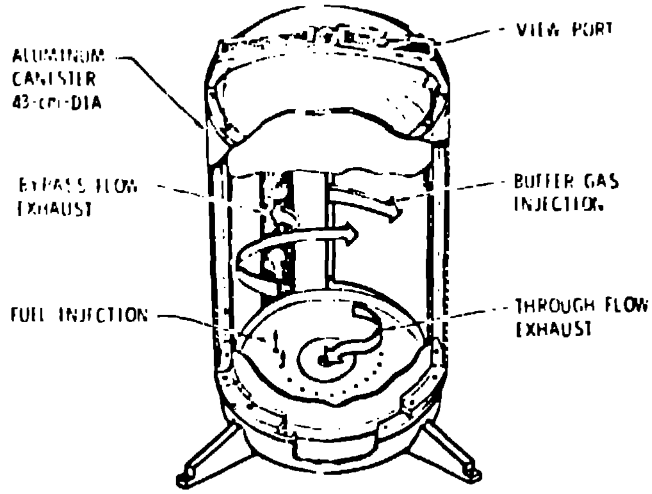

Fig. 6 - Fuel canister with buffer gas confinement

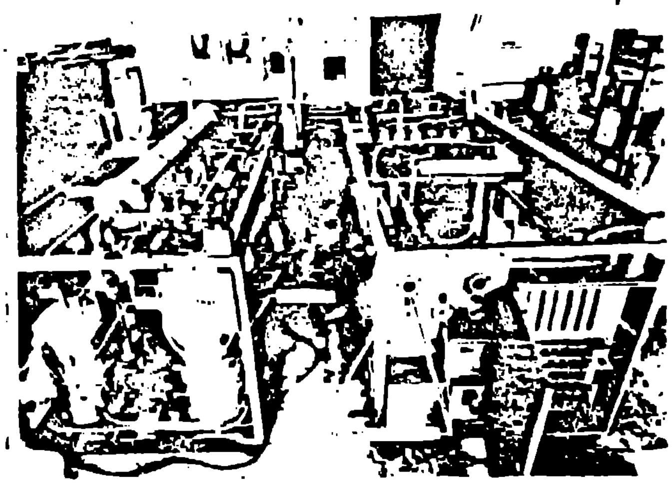

Fig. 7 - Vortex flow system for cavity reactor tests

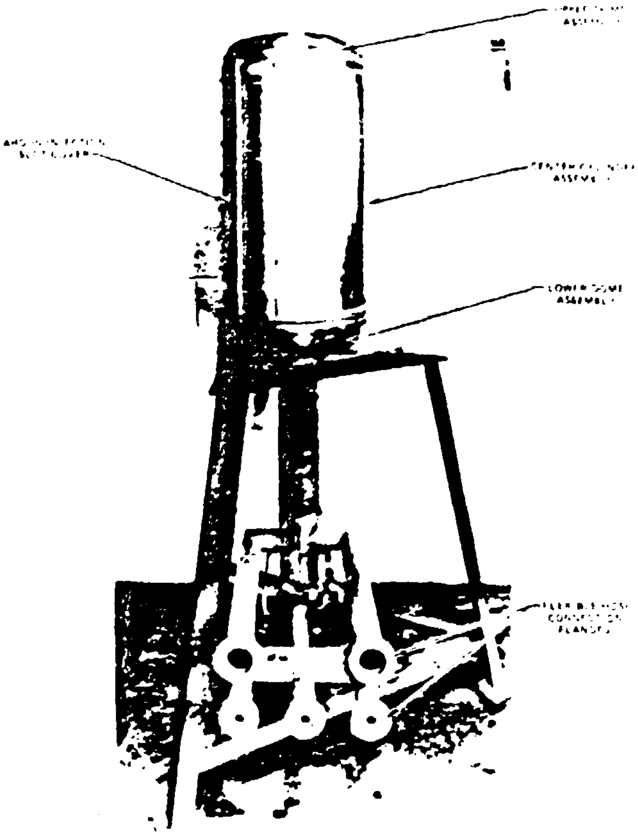

Fig. 8 - Vortex flow core canister assembly for cavity reactor tests

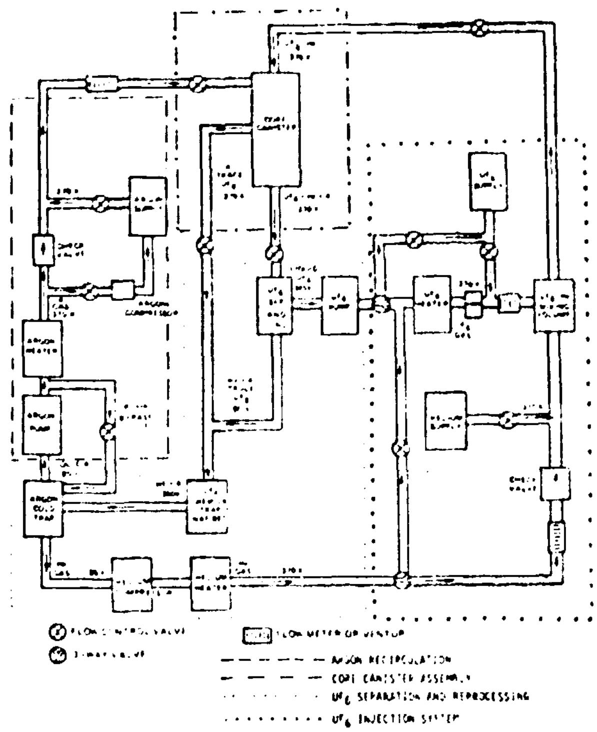

Fig. 9 - Schematic of confined Argon/UF6 flow system

flow exits through a perforated section in the canister wall after one sweep around the circumference of the canister. The remainder of the argon, along with the uranium hexafluoride fuel is removed from the canister through an exhaust port located at the center of the end wall. Injectors located just outboard of the exhaust port inject uranium hexafluoride continuously into the swirl pattern of the reactor core.

The effluent from the exhaust aperture is a mixture of buffer gas and gaseous fuel. Although initial critical tests will be made with gas flow in a blowdown mode, provisions are being made for continuous operation where the fuel and buffer gas will be separated on-line for loop operation.

A schematic diagram of the overall flow system, omitting cleanup devices for fission product removal, is shown in Figure 9. It consists of four major subsystems.(9) The first is the core canister with the vortex chamber, similar in size to the one used in the prior static and flowing uranium hexafluoride tests. The second is the argon buffer gas circulation system, the third is the uranium hexafluoride injection system, and the fourth is the uranium hexafluoride separation and reprocessing systems.

From the vortex chamber, most of the uranium hexafluoride fuel enters a separator and condensor in which the uranium hexafluoride will be desublimed and thereby separated from the argon and helium. Separated from the other gases, the uranium hexafluoride will be liquified and then pumped back to the injection pressure. The reclaimed uranium hexafluoride will then be reconditioned for reinjection into the core canister. The residual gases from the uranium hexafluoride separation will be stripped of any trace quantities of uranium hexafluoride by passing the gases through a NaF chemical trap. After the helium is separated from the argon in a cold trap, it is recompressed to injection pressures and is available to be added to the uranium hexafluoride for reinjection into the vortex chamber. In a similar fashion, the argon is reclaimed for continuous use as a buffer gas. The reprocessing of the uranium hexafluoride fuel stream with regard to separation of fission products and the handling of transuranium elements is not considered in this system. In the current uranium hexafluoride reactor experiments their quantities are too small for engineering studies. In addition, techniques for the reprocessing of nuclear fuel are well developed and only need to be optimized for gaseous-fuel reactor application.

REACTOR FOR POWER SYSTEMS

A system study was performed recently for the U.S. Energy Research and Development Administration (ERDA). (10) The objective of the study was to obtain preliminary design data for a gaseous fuel reactor power station optimized with regard to the physical safeguarding of fissile material. The principal ground rules for the study were that: (a) there should be a low fissile material inventory in the reactor, (b) low fissile material divertability, and (c) minimum fissile material transportation. The study developed a concept of a sustainer breeder reactor. That is, a breeder reactor with a breeding ratio of 1.0. This is achieved in the molten salt blanket shown in Figure 10, wherein thorium is converted to U233. The molten salt is continuously processed, extracting U233 and feeding it to the gas cores. The advantages from the non-proliferation standpoint is that once the reactor has reached a breeding equilibrium only fertile material, i.e. thorium, would be delivered to the plant. The design concept also includes a fuel cleanup system. This means that the fission fragment inventory is kept at a minimum since the fission fragments are continuously being removed from the system and could then be removed from the plant. The gas core concept obviates the problems that occur from the necessity of storing spent fuel elements as a conventional plant must.

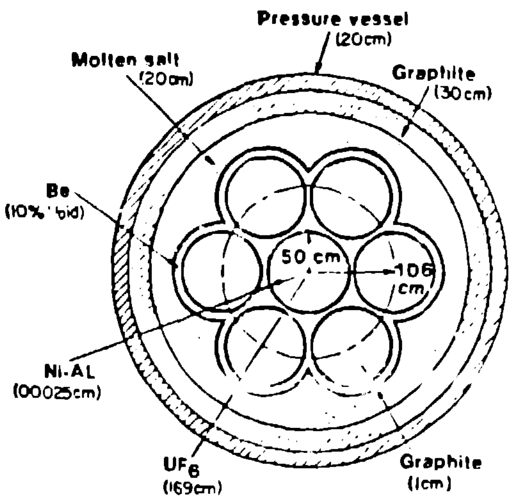

Fig. 10 - Schematic of mixed flow reactor

The study investigated two design concepts; one where heat is removed by gas convection and the second where the reactor is run at high temperature, the fuel is a uranium plasma and heat is removed by radiation. In the first concept, the mixed flow reactor, uranium hexafluoride and helium gas are intimately mixed and injected through a slot in the peripheral wall which extends along the entire length of the cavity. The flow enters tangentially and establishes a vortex flow within the cavity. A major fraction of the flow is withdrawn from the cavity through a perforated plate located in the cylindrical peripheral wall of the fuel cavity. The remainder of the injected flow spirals radially inward and passes out of the fuel cavity through central end wall exhaust ports. This flow resides within the cavity for a longer period of time than the flow removed through the peripheral wall. Because of the longer residence time in the cavity, it is heated to a higher temperature. The conceptual deisgn of this reactor gives an overall dimension of 5 m diameter and 9 m tall

The transfer of power from the reactor cavities is accomplished by the effluent of uranium hexafluoride -He mixture, which through a combination of high and low temperature heat exchangers delivers its energy to a gas turbine and a steam turbine loop, respectively. (11) The various flow circuits, including a fission product cleanup loop and a device for U233 fuel extraction from a thorium blanket, are shown in Figure 11, along with values of temperature and power at the various stations. Note that the low temperature secondary helium loop also removes heat from the beryllium moderator and the thorium blanket.

The reactor uses about 65 tons of molten salt and 24 tons of beryllium. The uranium hexafluoride and helium enter the power extraction loop at 1225 K. The heat is transferred to a secondary helium loop that drives a gas turbine. In the fission product cleanup loop a small fraction (10^{-4}) of the flow is bled from the fuel loop for cleanup. This reactor is sized at a power of .00 megawatts thermal. The inventory of U233 in the system is as follows: 45 kg are contained in the cavities, 4 kg heat exchangers, 16 kg piping, 2 kg circulator, 10 kg fission product cleanup loop, and 14 kg as necessary reserve for initial startup. The total plant inventory is 91 kg.

With respect to divertability, the entire inventory could be removed, but it would result in shutting the plant down. If, however, diversion were attempted by taking the freshly-made uranium hexafluoride, the reactor would become subcritical after removal of only 4 kg of uranium.

The second concept, the plasma reactor, was examined because of the possibility of higher efficiency. It also has a considerably lower fissile inventory. Since the plasma reactor fuel is uranium at 5000 K, an argon buffer gas is circulated in a vortex to keep the uranium away from the walls. The cells are configured as shown in Figure 12, however, the dimensions are somewhat smaller than those of the mixed flow reactor. The cell diameter is 1/2 m and the length of a cell is 1.85 m. The gases are not premixed. The argon is injected through the slit in the wall and the uranium through end wall ports located at a radius of 0.2 m. The exhaust is again through both side wall and end ports. Because of the smaller cavity size there is a dramatic reduction of all material weights. Only 16 tons of salt and 8 tons of beryllium are required. The fissile inventory in the system is as follows: 16 kg in the cavities, 3 kg in the separator, 1 kg in the fuel injection duct, 1 kg in the piping, 2 kg in the circulator, 22 kg required for initial startup reserves. The resulting total is 45 kg.

CONCLUSIONS

The gaseous fueled reactor system has the potential of several distinct advantages as an advanced power source. Because of these advantages it appears possible that this may be an ideal reactor for power production and for space propulsion. Characteristics such as high operating efficiency and low uranium inventory are particularly attractive. Advances in certain technology areas must be accomplished before it will be possible to produce an engineering design for a gaseous fueled power station. Corrosion problems of fluorine and uranium hexafluoride with materials must be solved, however, recent advances indicate these problems are not insurmountable. The vortex flow of buffer gas confinement obviates the most severe environment in the flow system. The feasibility of such confinement has been demonstrated

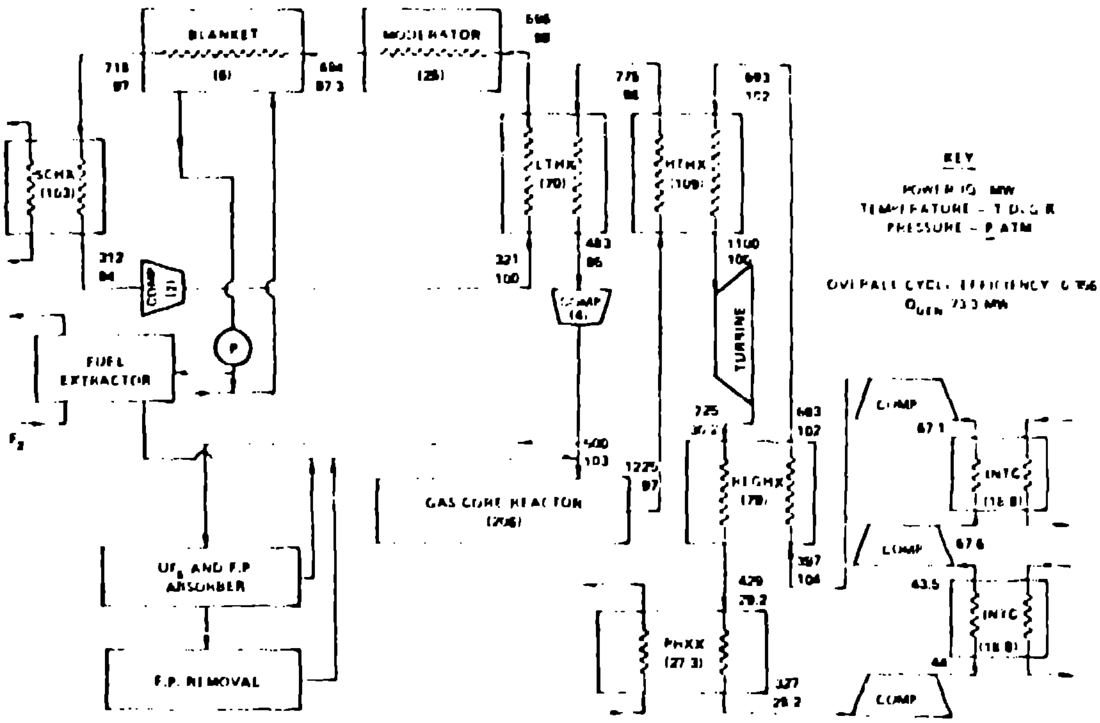

Fig. 11 - Mixed flow reactor power extraction loop

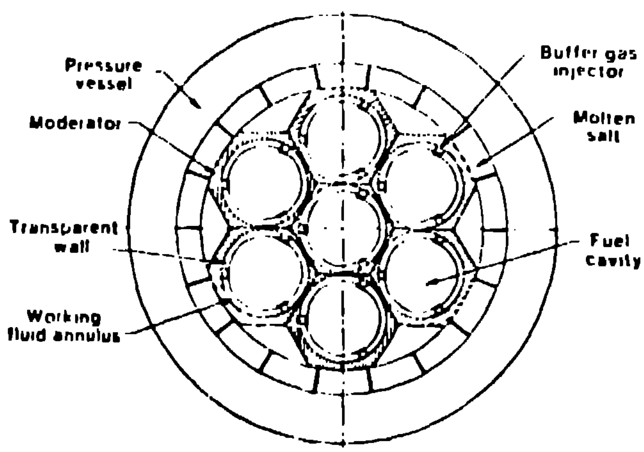

Fig. 12 - Schematic of plasma core reactor

successfully for small-scale devices and the present experimental activity is aimed at demonstration of the principle in the reactor environment at moderate power levels.

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